Getting around in the Arctic—what we do (and don’t) know about boundary currents

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What have we got to go on?
The Arctic plumbing diagram
- how do we know it?
- how good is it?
(Pacific Water Shelf Break (boundary) Currents)
The Arctic Ocean Boundary Current
How else can we move?

INFLOWS

Pacific Water through the Bering Strait
- shallow (0 - 50m)
- order 1 Sv
- comparatively fresh
- seasonally warm/cold

Atlantic Water through the Fram Strait and the Barents Sea
- deep (0 - 2600m)
- order 10 Sv
- comparatively salty
- warm

OUTFLOWS

Through Fram Strait
- Pacific, Atlantic and surface waters
- deep (0 - 2600m)
- order 10 Sv
- comparatively salty
- warm

Through the Canadian Archipelago
- Pacific and surface waters
- shallow (0 – few hundred m)
- order 1 Sv
- comparatively fresh

Arctic Bathymetry

Broad shelves
Deep Basins
Mid-ocean Ridges

IBCAD (International Bathymetric Chart of the Arctic Ocean)
Typical Arctic profiles

**Atlantic Water**
- Warmer, Salts
- Largest volume input

**Pacific Water**
- Nutrient rich
- Source of heat and freshwater

**Mixed Layer**
- Usually thin (no wind stirring)

**Bottom Water**
- "the rest"
- Western Arctic warms

**Atlantic Water**
- $T > 0^\circ C$, deeper than 200m
- $T_{max}$ and layer below
- Higher Salinities
- Radionuclide tracers
- Eastern Arctic warmer

**Pacific Water**
- High nutrients
- Shallow (<200m) $T_{max}$
- Comparatively fresh (<33 psu)
- Shallow (<200m) $T_{max}$
- Mostly only in Western Arctic

**MIXED LAYER**
- Usually thin (no wind stirring)

- Pacific and Atlantic in T-S Space
- Density determined mostly by salinity at $T < 2$ deg C
Arctic Plumbing

AW circulation very different to PW circulation
- AW follows topography (with exceptions?)
- PW follows ice ??

Jones et al., 2001, Polar Research

Pacific Water Shelf Break jet

Pickart et al., submitted, 2010

ATLANTIC LAYER
- warm, salty
- largest volume input

How we know what we think we know
What we think we know
Some possible explanations

Aagaard, 1989
- topographically steered boundary current along slopes and ridges
  - interior flow weak, dominated by eddies
  (based on current meters)

Rudels et al., 1994
- mixing off St Anna
  - cyclonic (anti-clockwise) circulation
  (based on T-S and tracers)
Atlantic “Branch Waters” (BW) Fram Strait (FSBW) and Barents Sea (BSBW)

**ATLANTIC LAYER**
- temperature > 0 deg C
- FSBW and BSBW
- usually between 200-1000m in water column
- Tmax usually between 200 and 500m depth

FSBW - temperature max

BSBW - inflexion pt

**Changing AW**
1990 Rossiya tourist cruise, XBT section
Significant Warming of AW

**Warming in the Arctic**
Quadfasel et al., Nature, 1991

**Atlantic Layer warming in 1990s**
(collation/model by Karcher et al., 2003)

Modelled (full fields) and observed (circles) AW core temperatures in various years

Warmer since 1990s, .... but slight cooling following the warming ... USE THIS AS TRACER!!

FSBW enters through Fram Strait, surface cools, (may melt ice, may freeze). FSBW TRANSFORMED to subsurface Tmax

Along SLOPE may be capped with ice melt, or perhaps shelf waters

At St ANNA BSBW outflow mostly comes in at depth, into FSBW core, below it (maybe above)

AW does not really subduct below Arctic Surface Waters. Instead they are formed from AW.
AW warming spreads also into Western Arctic

Tmax from submarine cruises
See warming, but data very sparse

Tracers of Atlantic Water

- TEMPERATURE-SALINITY
  - presence of Tmax
  - form in TS space
  - following a warming

- CHEMICAL TRACERS
  - usually atmospheric source
  - mixed into surface water, and then isolated from the atmosphere

  CFCs (Chlorofluorocarbons)
  - solvents from 1960s onwards
  - CC4 (“carbon-tet”) is oldest
  - then CFC11, CFC12 and newest CFC113
  - atmospheric concentrations KNOWN
  - use presence or ratios to give age

  Cs and I from Nuclear Reprocessing
  - on-going
  - concentrations KNOWN
  - use presence or ratios to give age

  Bomb Tritium
  - atomic bomb tests 1950s
  - surface layer of tritium (isotope of H)
  - decays to Helium-3 (half-life ~ 12.4 yrs)

- NON-CONSERVATIVE (weakness and strength)
- CONSERVATIVE
  - but mixing important

Seasonal Atlantic Water Variability

- amplitude ~ 0.5 deg C!!
- aliasing problems with CTD sections
- different timing at depth

~840 m, i.e. Barents Sea Branch

~260 m, i.e. Fram Strait Branch

Bringing it back to observations

- Equivalent barotropic Flow Structure
- mean ~ few cm/s, plus stronger eddies
- ~5 ± 1 Sv split into 2 by the Lomonosov ridge
- found over 500-3000m depth contours
- 50-100km wide

Woodgate et al, in press
.. also in models

Karcher et al., 2007
- 3 of the “best” Arctic models

.. state-of-the-art models are inconsistent about direction of circulation in the Western Arctic!!

What drives the Boundary Current?

Greg Holloway “Neptune” effect
(Holloway, 1987; Nazarenko et al, 1998)

Eddy-topography interactions drive a mean along isobath flow

- makes model look like our bias, BUT IS TUNED
- can we quantify this effect given number of eddies?
- “topostrophy” = “v x grad D” = tendency of flow to follow topog (Holloway et al, 2007)

PROPERTIES TO EXPLAIN:
- equivalent barotropic structure
- steered by topography - weak
- variability NOT local - width (~ 100 km)
- pathways - variability - direction

Taking things down to “basics”

Barotropic

Fully non-linear model,
7.5km resolution
Constant in and out flows
No surface forcing

Yang, 2005

PV of inflows?

The Arctic and Subarctic Ocean Flux of Potential Vorticity and the Arctic Ocean Circulation
JPO, 2005

| Table 1: Arctic and subarctic ocean flows in the standard run. |
|-----------------|-------|-----|----------|
| PV flux (m²/s³) | Volume (Sv) | sill-depth (m) |
| 0.85 | 80 | 106 |
| 1.26 | 100 | 140 |
| 2.08 | 150 | 200 |

+ve PV total = cyclonic

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| Table 2: Arctic and subarctic ocean flows in the modified run. |
|-----------------|-------|-----|----------|
| PV flux (m²/s³) | Volume (Sv) | sill-depth (m) |
| 0.85 | 80 | 106 |
| 1.26 | 100 | 140 |
| 2.08 | 150 | 200 |

-ve PV total = anticyclonic

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Cyclonic/Anticyclonic depends on Potential Vorticity balance of in and out flows

<table>
<thead>
<tr>
<th>PV Flux</th>
<th>Transport x PV where PV is</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bering Strait inflow</td>
<td>1078</td>
</tr>
<tr>
<td>Barents Sea inflow</td>
<td>0796</td>
</tr>
<tr>
<td>Fram Strait inflow</td>
<td>0.190</td>
</tr>
<tr>
<td>Fram Strait outflow</td>
<td>-0.200</td>
</tr>
<tr>
<td>Total</td>
<td>1.780</td>
</tr>
</tbody>
</table>

But .. there is also a PV source from surface stress

PV Flux = Transport x PV where PV is

\[
\frac{f + \zeta}{H}
\]

So – Bering Strait and Canadian Archipelago balance approximately

- What goes in Fram Strait, comes out

Difference lurks in Barents Sea flux, which comes in as shallow water column (PV high) and goes out as a deep water column (PV low)

THUS – expect incoming PV higher than outgoing PV - thus cyclonic

Bringing it back to f/H contours

Simple theory, Ekman pumping and hydrographic forcing from climatology

Boundary Current
- topographically steered
- forced by wind stress from Nordic Seas

Atlantic Water zigzags AOS94

Line up/ Nest all through the Arctic - ~ 5,000km

Angles of the Zigzags match double diffusive theory

Carmack et al, 1997

But .. there is also a PV source from surface stress

Karcher et al, 2007

Primitive equation model, within an Atlantic water density layer

In Eurasian Basin
- PV forcing from Barents

In Canadian Basin
- surface PV forcing

Yang, 2005

But .. there is also a PV source from surface stress

Karcher et al, 2007

Primitive equation model, within an Atlantic water density layer

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Yang, 2005
Mixing and Double Diffusion in T-S Space

In double diffusive processes, heat diffuses faster than salt. So, in TS space resultant waters are not on a straight line between the parent water masses.

Mechanical mixing in TS space creates straight lines between water masses.

Salt fingering Regime
Warm Salty / Cold Fresh unstable in salt

Diffusive Convection Regime
Cold Fresh / Warm Salty unstable in temperature

Temperature unstable
Salinity unstable

“T-S Zigzags” in the Arctic

Interaction of two water columns - therefore can learn something about origins

Line up throughout Arctic (~ 5000km) - therefore LOW ENERGY environment

Spread by??
- self propagating? (spread at 90deg to front)
- fossil intrusions? (carried advectively)

Can be used as a tracer of the boundary current???

Many refs.
- most Carmack, Walsh or McDougal
  for overview, see Woodgate et al, 2007

The Warming of the 1990s

1993 Larsen - 1 deg warmer on the Mendeleev Ridge
- inversions in temperature and salinity
  Carmack et al, ’95, and McLaughlin et al, ’96

Figure 7: Isopleths of the potential temperatures (°C) showing the core of Atlantic water within the Arctic basin (shown by ‘resolution’ line) and the surrounding line of mean potential temperature (°C) at 200 m. The map was drawn using Larsen’s data (Larsen, 1962). 

Figure 8: Vertical profiles of the hydrographic section at the latitude of the Chukchi Sea (74°E). The upper section shows a strong signal of Atlantic water (Larsen, 1962).
Zigzags – do tracers agree with this??

Higher Oxygen and CFCs in the warmer, saltier part of the zigzags

% Oxygen Saturation

CFC-11

Temperature Salt Oxygen CFC-11

Woodgate et al., 2007

Chukchi Borderland Atlantic Water Circulation

Only shown Fram Strait Branch Water, but Barents Branch very similar

Woodgate et al., 2007, JGR

http://psc.apl.washington.edu/HLD

Now do it in time

McLaughlin et al, 2009

Warm waters rounding the Chukchi Rise,
ALSO – intrusions spreading into Beaufort

Leaky Boundary Current??

The Arctic Ocean Boundary Current
- the Pan-Arctic Circulation of Atlantic Water

Observations
- tracers, current meters
- topographically steered
- equivalent barotropic
- ? eddies
- quantify properties
- role of double diffusion?

Plumbing diagrams
- PW and AW v different
- how good are they anyhow
- variability?

Theory
- f/H contours, PV forcing
- Barents sea, local and far field wind stress
- Eddy topography interactions (Neptune)

Models
- Eurasian Basin – some agreement
- Canadian Basin – lots of disagreement